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NEW CONCEPTS FOR SOLID STATE MICROWAVE GENERATORS

Report No. 3

Contract No. DA 36-039-AMC 00001(E)

Project No. DA 3A99-21-001

Period Covered

Third Quarterly Report

1 April 1963 to 31 June 1963

U. S. Army Electronics Agency

Fort Monmouth, New Jersey

Shockley Laboratory
Clevite Transistor Division
Clevite Corporation
Palo Alto, California

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Report Prepared By

R. M. Scarlett

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NEW CONCEPTS FOR SOLID STATE MICROWAVE GENERATORS

1. PURPOSE

The purpose of this contract is to extend the application of solid-state devices in the microwave region. To this end, specific devices, in particular the transit-time delay diode, are to be explored for their theoretical potential and practical capability.

2. ABSTRACT

A new design of transit-time device having minimum unused area is described. The first experimental units showed abnormally high emitter capacitance at low forward bias and low cutoff frequency which is not yet understood. Previous theory of the optimum operating frequency is modified and corrected.

New small-area PIN diodes made epitaxially with antimony doping showed a transition time of about 0.5 nsec at a 2.4 ampere extraction current. At this current level, they appear to be limited by carrier storage effects rather than by capacitance.

3. PUBLICATIONS, ETC.

Monthly performance summaries and two quarterly reports have been delivered to the contracting officer as required.

4. FACTUAL DATA

4.1 Transit-time Delay Diodes

4.1.1 New design

The basic theory and preliminary experiments on transit time devices have been presented in preceding quarterly reports. An important difficulty with the devices described there arises from their relatively large ratio of total collector-base area to active area. As outlined in the previous report, this large ratio can lead to excessive losses in the base sheet resistance. A new design employing appropriate geometry to reduce this ratio has been undertaken.

The new design makes use of standard planar diffusion technology in silicon. It consists of two emitter stripes on either side of a central base stripe. The ratio of total collector-base area to active area is less than 1.7 in contrast to a ratio of 5 obtaining in previous experimental devices. The basic geometry is shown in Fig. 1, which indicates the areas of base diffusion, emitter diffusion, and aluminum metallizing. Emitter and base aluminum contacting areas overlap onto the oxide at either end of the device to allow the bonding of gold ribbon leads. Three different sizes of device are incorporated in one mask to test the effects of different areas and stripe widths. The pertinent dimensions of these three devices are given in Table I.

	Emitter stripes		Base Area
	Length	Width	
Large	500 μ	65 μ	530 x 205 μ
Small	250	65	280 x 205 μ
Medium	250	100	280 x 275 μ

Table I Transit-time device dimensions

The width of the emitter stripes is determined by the lateral voltage drop in the base layer, which produces the well known emission crowding effect. According to the analysis in the preceding report, a typical base sheet resistance of 120 ohms per square results in an effective emitter width of about $80\ \mu$ for a base current of 50 ma per centimeter of periphery. The emitter stripes should be made equal to or narrower than this effective width; otherwise unused emitter area exists which can result in power dissipation at high signal levels. One attractive feature of the transit time device is that the degree of emission crowding should be much less than in a conventional transistor. This is because, in principle, large rf lateral base currents are not present in the transit time device.

The base layer width was initially chosen to be of the order of $2\ \mu$ for operation around 1.5 Gc in accordance with the relation developed in Eqn. 6 of the last quarterly report. However, as discussed below in Section 4.1.4, the approximation used in deriving this relation is valid only for impractically large fields in the base, and a more appropriate base width would be $3\ \mu$.

4.1.2 Diffusion data

The principal diffusion data for the initial devices of the new design are given in Table II along with parameters deduced from electrical measurements to be discussed later. In addition to the new geometry, the following changes have been introduced in the diffusion schedules as compared with those used for previous devices. Run no. 10 has a heavier base doping than run no. 9 (see the previous report) achieved by slightly higher predeposition temperature and the use of a slightly longer emitter diffusion to compensate for the drop in β which results from heavier base doping. This was undertaken to try to achieve a stronger built-in field in the base layer.

However, an unusually low β resulted. In run no. 11 the base doping was reduced, giving a β of about 3 and a rather high emitter capacitance. The f_t frequency is unaccountably low on these devices, which may result in part from the higher emitter capacitance but probably has another cause as yet undetermined. Run no. 12 was made with increased oxide thickness to reduce the capacitance (2 to 3 picofarads) existing between the metal contacting areas through the oxide layer to the collector body. This effort to obtain increased oxide thickness was abandoned because of severe cracking which occurred. In run no. 13 a heavier emitter diffusion is used to further raise the current gain β . This expedient also resulted in a thinner base layer and higher f_t frequency than run 11, but this frequency is still lower than can be satisfactorily explained.

4.1.3. Experimental results

Some experimental measurements on the new devices are indicated in Table II.

The emitter-base capacitance follows a $1/c^3$ law with voltage from a few volts reverse to approximately zero bias. This indicates a linear graded junction whose slope "a" was calculated to be that shown in Table II. These values of "a" are quite reasonable from the diffusion parameters. It can be seen that run 11 has approximately three times the slope of runs 10 or 13 on account of its heavy base diffusion and relatively shallow emitter diffusion. In the forward bias range the emitter-base capacitance increases more rapidly than the $1/c^3$ law would indicate, and the reason for this is not yet understood. Typical values are 140 picofarads at 200 millivolts forward bias, and 700 picofarads at 300 millivolts. This rapid increase in capacitance might be attributable to the onset of injection capacitance, as treated for example by Morgan and Smits.¹ However, calculations based on the gradient a show that the junction does not become neutral until forward

TABLE II
DIFFUSION PARAMETERS

Run No.	10	11	13
Collector thickness	7.8 μ		
Collector resistivity	1.06 Ω cm		
Boron predeposition	30 min 1050 $^{\circ}$ C		
V/I	--	2.8 Ω	3.2
Boron diffusion (steam)	90 min 1200 $^{\circ}$	60 min 1200 $^{\circ}$	60 min 1200 $^{\circ}$
V/I	--	5 Ω	11
xj	--	3.2 μ	4.3
Phosphorus diffusion	35 min 1050 $^{\circ}$	30 min 1050 $^{\circ}$	25 min 1100 $^{\circ}$
V/I	--	0.4 Ω	0.4
w _b	--	2.1 μ	1.5
Beta	very low	3	10
C _e 1 volt	1.2 x 10 ⁵ pf/cm ²	1.6 x 10 ⁵	1.1 x 10 ⁵
a	1.3 x 10 ²³ cm ⁻⁴	3 x 10 ²³	1 x 10 ²³
f _t	90 Mc	40 Mc	80 Mc
N _b w _b	--	1.1 x 10 ¹⁴	2.2 x 10 ¹³ cm ⁻²

biases of the order of 700 millivolts are reached, and injection capacitance is not expected to become important until then.

Another mysterious point is the low value of f_t . This frequency is defined in the usual way as the frequency at which the common emitter current gain becomes unity. It can also be shown to be the frequency at which the real part of α (common base current gain) becomes one-half of its zero frequency value. This frequency is used as a convenient reference point which is relatively easy to measure, and some aspects of it are discussed in the following section. According to the theory of the current gain, f_t for a drift transistor is greater than the characteristic frequency f_o , defined below. This frequency f_o should be at least of the order of 100 Mc or more for a 2 μ base width, even allowing for a severe degradation in minority carrier diffusion constant because of a high doping prevailing throughout most of the base layer. A built-in field corresponding to a ratio of doping at the emitter and collector sides of the base layer of about 50 (m value of about 4; see section 4.1.4 below) should result in an f_t frequency of about 270 Mc. This expected value is 3 to 4 times higher than the measured values given in Table II. By observing the behavior of f_t with emitter current, one can see the influence of emitter capacitance at currents below about 10 ma, and calculations made from these measurements indicate that the effective emitter capacitance is about 140 pf for the smallest area device. This value is reasonable from extrapolated emitter capacitance measurements made under reverse bias but does not agree with the much higher measured emitter capacitances obtained at small forward biases. Moreover, above 10 ma f_t becomes substantially independent of emitter current up to the maximum current used of 100 ma. An examination of the magnitude of the current gain where its phase is 90° (see section 4.1.4) indicates that rather small effective m values are present, probably less than 1. This means that the built-in drift field in the base is somehow ineffective in these particular devices. Further experiments and diffusion runs duplicating those previously made are planned.

Because of the possibility that parasitic elements in the device and in the package were affecting current gain measurements, an investigation of these was undertaken. Figure 2 shows a tentative equivalent circuit for the device showing the principal parasitic elements. The elements C_{ec} and C_{bc} are the capacitances existing through the oxide layers from the metal bonding areas and are of the order of 2 to 3 pf each. The lead inductances of the TO18 package L_b and L_e are of the order of 2 nh. In conjunction with the parasitic capacities these inductances will distort the apparent current gain measurements above about 600 Mc, but they should not affect the measurements at or near the f_t frequencies of from 50 to 100 Mc.

As a check on the diffusion schedules, measurements of collector current as a function of emitter-base forward bias were made. These yielded points falling on the familiar slope of 59 mv per decade of collector current, and from this one can calculate the total amount of doping in the base layer per square centimeter. The calculated values are given in Table II and agree reasonably well with what one would expect from the diffusion data. Note that run 11 has about five times more charge in the base layer than runs 10 and 13 because of its heavier base diffusion and shallower emitter diffusion.

4.1.4 Modified expression for operating frequency

The theory of the transit time delay device is based on the transport of minority carriers by drift and diffusion across the base layer. An analytical expression for the transport factor was first derived by Shockley² for a case of an exponentially graded base, and no large deviations from this expression are expected for error function or gaussian base distributions. This transport factor depends on two parameters, one giving the base grading and the other giving a frequency characteristic of the base layer width:

$$m = \ln N_1 / N_c = \Delta V / (kT/q) \quad (1)$$

$$\omega_o = 2D/w_b^2 \quad (2)$$

In Eq. 1 N_1 is the base layer doping next to the emitter, and N_c is the base layer doping at the collector. In Eq. 2 D is the minority diffusion constant, and w_b is the base layer width. In terms of these parameters the transport factor α can be written

$$\alpha = \frac{4 \psi \exp m/2}{(m + 2 \psi) \exp \psi - (m - 2 \psi) \exp (-\psi)} \quad (3)$$

where

$$\psi = \frac{m}{2} (1 + 8 j \omega / m^2 \omega_o)^{1/2} \quad (4)$$

Calculations of the maximum negative resistance given in Eq. 5 of the first quarterly report were based on the above function and are believed to be accurate. However, estimates of the frequency at which this negative resistance occurs, which is about the same frequency where the phase is 225° , were based on assuming the phase of α to increase linearly with frequency according to $\omega \tau_b$, where τ_b is the drift time through the base (see Eq. 4 of the first quarterly report). This assumption is true only for small values of ω/ω_o when α reduces to the following form for $m > 3$:

$$\alpha \approx \exp(-2 j \omega / m \omega_o) \quad (5)$$

It can be verified that $2/m\omega_o$ is the drift time τ_b . However for large ω/ω_o α approaches:

$$\alpha \approx 2 \exp[m/2] \exp[-(\omega/\omega_o)^{1/2}] \exp[-j(\omega/\omega_o)^{1/2}] \quad (6)$$

where it can be seen that the phase angle increases as the square root of frequency, and that α approaches its $m = 0$ value times a factor $2 \exp m/2$. In this range diffusion dominates the phase angle while the drift field provides a large amplitude. This means that a frequency based on linear increase of phase is underestimated.

Calculations based upon Eq. 3 for the frequency at which 225° phase occurs give the numbers shown in Table III. It is seen that this frequency is not a strong function of m in keeping with Eq. 6, and for practical drift fields having m values from 4 to 6 this frequency is about 20 times the characteristic frequency ω_0 . The present accurate calculation gives values order of twice the frequency estimated on the basis of a linear phase relation.

For purposes of treating experimental data it is convenient to have other points of reference. One of these is the amplitude of α when its phase is 90° and the frequency at which this occurs from which one can find m and ω_0 . Another point is the frequency of unity common emitter current gain, denoted by ω_t , which is sometimes a convenient quantity to measure. The numbers corresponding to these points are given in Table III. Most of these were obtained graphically from plots of Eq. 3 given by Das and Boothroyd.³

4.2 PIN Charge Storage Diodes

In this phase of the contract there are two developments to report. One is the use of improved circuitry having smaller stray inductance for observing the transition time of the diodes. This has resulted in considerably cleaner waveforms. The second development is the fabrication of smaller area p-i-n diodes than previously used in an effort to reduce the diode capacitance which was believed to be limiting the transition time. Some of these new diodes are made on antimony doped epitaxial material to give a sharper $N^- N^+$ interface.

TABLE III
CURRENT GAIN REFERENCE POINTS

	m	0	2	4	6
-90° phase	ω/ω_o	2.5	3.3	4.6	6.1
	$ \alpha/\alpha_o $	0.43	0.53	0.64	0.72
-225° phase	ω/ω_o	17	17.5	19	21
	$ \alpha/\alpha_o $	0.04	0.07	0.12	0.17
	ω_t/ω_o	1.0	1.76	2.67	3.6

$$m \equiv \ln N_1 / N_c$$

$$\omega_o = 2 D / w_b^2$$

4.2.1 Fabrication of small PIN diodes

P-i-n diodes were made on different types of epitaxial material. Run no. 7 was made on Merck material having an N⁻ layer thickness of about 8 μ and a specified resistivity of about 14 ohm-cm on a much more heavily doped N⁺ substrate. The doping agent is presumably phosphorus, and the sort of doping profile obtained by capacity measurements on a finished diode, using the method described in the first quarterly report, is given in Fig. 3 for the curve labeled 7-3. A gradual increase in doping is observed reaching a level corresponding to about 5 ohm-cm at a distance of 3.5 μ from the junction, and becoming a very rapid increase about 4.5 μ from the junction.

Run no 8 was made on epitaxial material grown in the Shockley Laboratory and consisting of a 9 ohm-cm film of 4.8 μ thickness on a 0.02 ohm cm substrate. The doping agent employed in this case was antimony, which has been found to give a much smaller "autodoping" effect than phosphorus.⁴ This autodoping effect involves the transfer of dopant from the solid to the ambient gas phase and redeposition in the growing layer, and limits the sharpness of doping profile which can be obtained in epitaxial films.⁵ This mechanism is in addition to diffusion, which will also provide a limit on the sharpness.

The appropriate epitaxial slice was diffused with boron for five minutes at 1200°C using an open boat method. This resulted in a junction depth of about 1.8 μ and a surface concentration of 10^{21} . After diffusion, aluminum was evaporated through a mask to make aluminum dots on the P layer of diameter 0.25 mm. These aluminum dots were alloyed at 585°C. The diodes were then diced, using a wax dot of 0.4 mm diameter and CP 8 etch, and mounted in TO18 packages. Previous diodes were about 1 mm in diameter.

The doping profile obtained with the antimony doped epitaxial material is shown in Fig. 3 in the curve labeled 8-3. A considerably thinner N^- region is evident as compared with run 7 because of the thinner epitaxial layer which was initially employed. The N^- layer is sufficiently thin that useful information about the sharpness of the transition from n to n^+ is not readily obtained. A breakdown voltage averaging 80 volts was obtained on devices from run 8 corresponding to a field in the 1.5μ thick N^- region of approximately 5×10^5 volts/cm, which is about the expected avalanche breakdown field.

4.2.2 Experimental results

The transition time from on to off of the diodes is observed in the circuit of Fig. 4. The diodes are provided with a dc bias to initially bias them on, and they are turned off by an avalanche pulse generator driving the diode through a length of 50 ohm cable. This pulse generator⁶ employs a selected Shockley power transistor and can provide 5 ampere pulses rising in about 2.5 nsec. This rise time is probably limited by the inductance of the transistor leads inside the package.

A series 50 ohm resistor at the pulse generator can be inserted or removed to control the pulse current flowing into the diode. The .001 mfd capacitor is initially charged to about 120 volts. When the pulse generator fires, a current pulse of either 1.2 or 2.4 amperes travels down the 50 ohm line to the diode, depending upon whether the 50 ohm series resistor is present. With the diode connected in the shunt mode, a very low impedance is presented to the pulse until the carriers from the diode are extracted. Thus the current at this point doubles and a reflected current wave travels back toward the pulse generator. The current in the diode is therefore either 2.4 or 4.8 amperes. The connecting cable is chosen to be long enough, in this case three feet, that further reflections from the pulse generator do not

arrive back at the diode until well after the transition has taken place. This feature was not present in the previous circuit arrangement.

For the case of the series mode connection, the incident current pulse sees essentially a 50 ohm load, i. e. the input resistance of the 40 db attenuator, and no reflection occurs until the transition takes place. Thus the current in the series mode is either 1.2 or 2.4 amperes.

In the shunt mode one is observing essentially the voltage across the diode, and in the series mode one observes the current through the diode. The shunt mode provides a pulse with a rapid leading edge, and the series mode a pulse with a rapid trailing edge. The pulse is observed on a Hewlett-Packard sampling oscilloscope having a rise time of the order of 0.35 nsec.

In Fig. 5 are shown waveforms obtained in the new circuit for diodes which were previously described in the first quarterly report. Diode 2-5 is a "small area" diode, shown in Fig. 10 of that report; and diode 5-2 is a "large area" diode of the same general type as that shown in Fig. 11 except that it has considerably shorter lifetime. It is seen that the present waveforms are very much cleaner and easier to interpret. Diode 2-5 has an average capacitance in the reverse direction of about 15 pf. Since it is effectively being fed from a source impedance of 25 ohms, one expects an RC time constant of about 0.37 nsec, which would produce a rise time of roughly 0.8 nsec, which is quite close to that observed in Fig. 5. The rise time will be slightly modified by the package inductance, which is estimated from the 10 volt bump on the initial part of the response to be about 5 nh. Diode 5-2 has a capacitance of 40 pf, from which one would expect a rise time of 2.2 nsec and little influence from the diode package inductance. This is very close to what is observed from Fig. 5. Upon doubling the current through the diode by removing the 50 ohm resistor near the avalanche pulse generator, one observes that the rates of rise approximately double, as would be expected when driving

a capacitive load with double the current. One can therefore conclude that these two diodes are limited in their speed primarily by their capacitance at the particular current levels employed here.

Figure 6 shows the response characteristics of a diode from run no. 7, described in the previous section. This diode has an average capacitance of about 4 pf, which according to the previous reasoning should result in a transition time of the order of 0.2 nsec. It is evident that much larger values are observed, and at the higher current levels there is a slow initial portion to the turn-off transition which is probably caused by residual carriers in the device. These residual carriers can be expected to be important by virtue of the relatively wide N^- region (see Fig. 3) and the relatively gradual transition from N^- to N^+ . It is interesting to note that the slow initial portion of the transition seems less important when the diode is used in the series mode with a lower extraction current.

Diode 8 has also a capacitance of about 4 pf but a much faster response time than Diode 7 because of its narrower N^- region. The response time is still greater than one would expect on the basis of the capacitance alone, although the rise time limit of the oscilloscope is being approached. There is some evidence of residual carriers present at the higher current levels. When the extraction current is doubled, the response time of the diode does not decrease by a factor of 2 but rather by a factor of about 120/75, as estimated by the maximum rates of rise. This may be the oscilloscope limit coming in, and it may also be a reflection of the fact that the transit time across the N^- layer for space charge limited flow is inversely proportional to the square root of the extraction current, as expressed in Eq. 28 of the first quarterly report. It is probably safe to conclude that diodes 7 and 8 are not limited by their capacitance at these current levels but rather by internal mechanisms of carrier flow. Further accurate investigations would require the use of lower inductance packages and a faster oscilloscope for observing the response.

5. CONCLUSIONS

A number of samples of the new design of transit time device employing more optimum geometry have been fabricated. Diffusion schedules modified for higher base fields were employed. These devices have cut-off frequencies lower by a factor of 3 to 4 than the calculated values, and it appears as if the built-in field in the base layer is largely inoperative. The reason for this is not yet understood. Other measurements, such as those of capacitance and total doping in the base layer, appear normal.

P-i-n diodes having areas smaller by a factor of 4 than those made previously were fabricated. The use of antimony doped epitaxy probably resulted in sharper transitions from N- to N+ regions. In contrast to previous diodes, the response times on these units do not appear to be limited by their capacitance but rather by carrier storage effects. Rise times of the order of 0.5 nsec were obtained at a current level of 2.4 amperes. This performance is maintained out to forward currents of 200 ma.

6. PROGRAM FOR NEXT QUARTER

Further experimental models of the new transit-time device geometry will be made with different diffusion schedules in an effort to understand the low cutoff frequencies obtained. The emphasis will be on producing devices having useable amounts of rf power output.

7. PERSONNEL

The following personnel contributed to work on this contract during the third quarter.

Senior Scientists

R. M. Scarlett

M.S.R. Heynes

Associate Scientists

M. Yamada

L. Johnson

Technicians

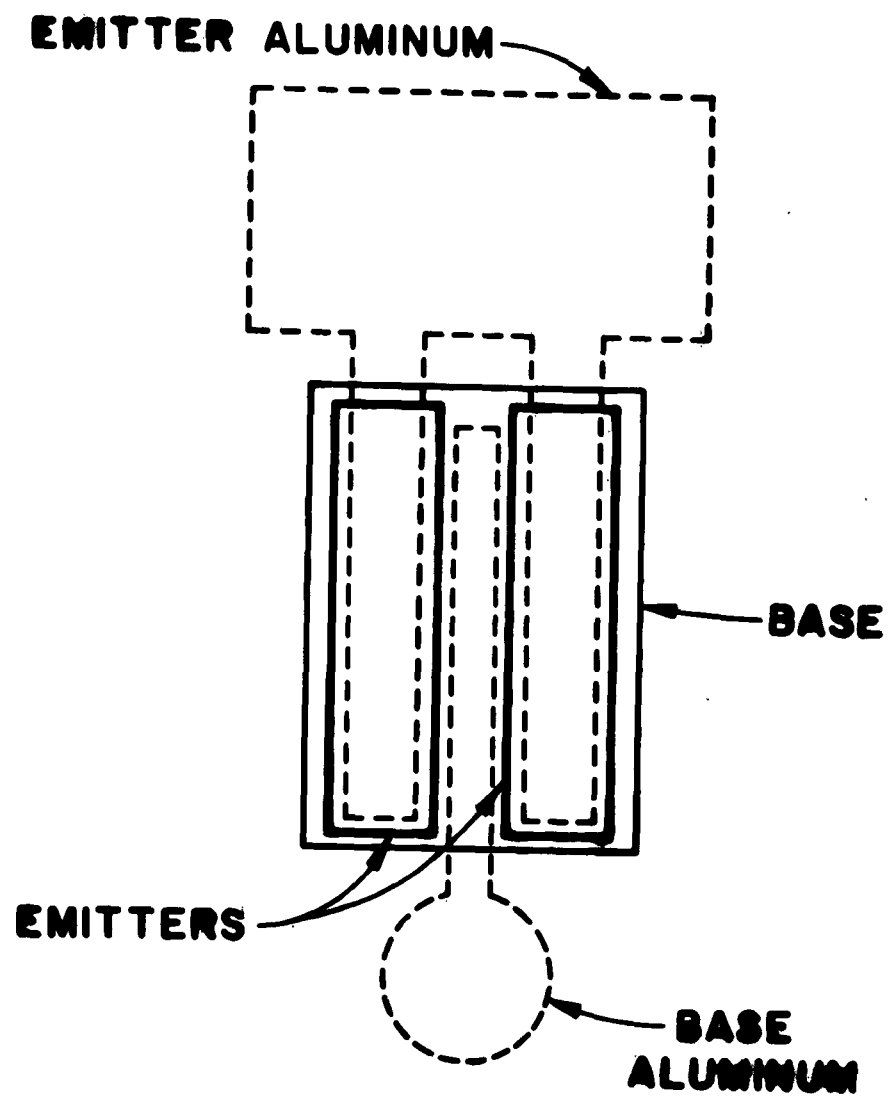
R. Julien

F. Topor

R. Cheek

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3. M. B. Das and A. R. Boothroyd, IRE Trans. on Electron Devices, ED-8, 15 (1961)
4. M. Heynes, unpublished memorandum
5. C. O. Thomas, D. Kahng and R. C. Manz, JECS 109, 1055 (1962)
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25μ

Fig. 1 Transit-time device geometry

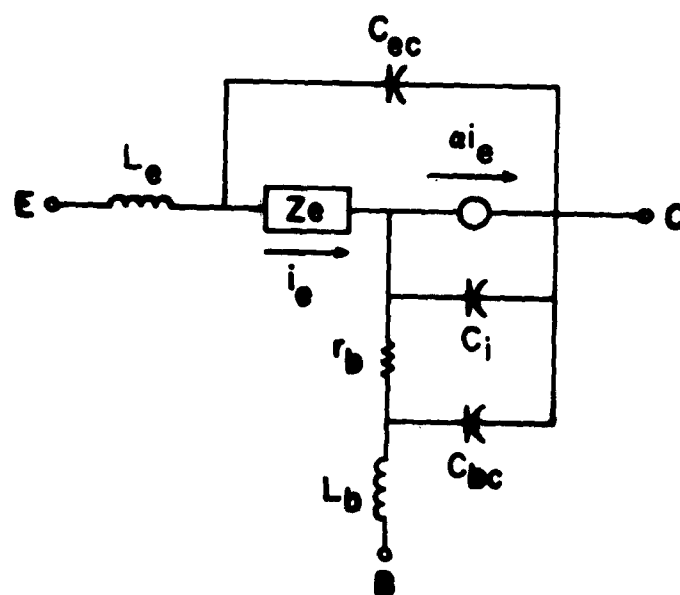


Fig. 2 Transit-time device equivalent circuit

8-2-63
50683

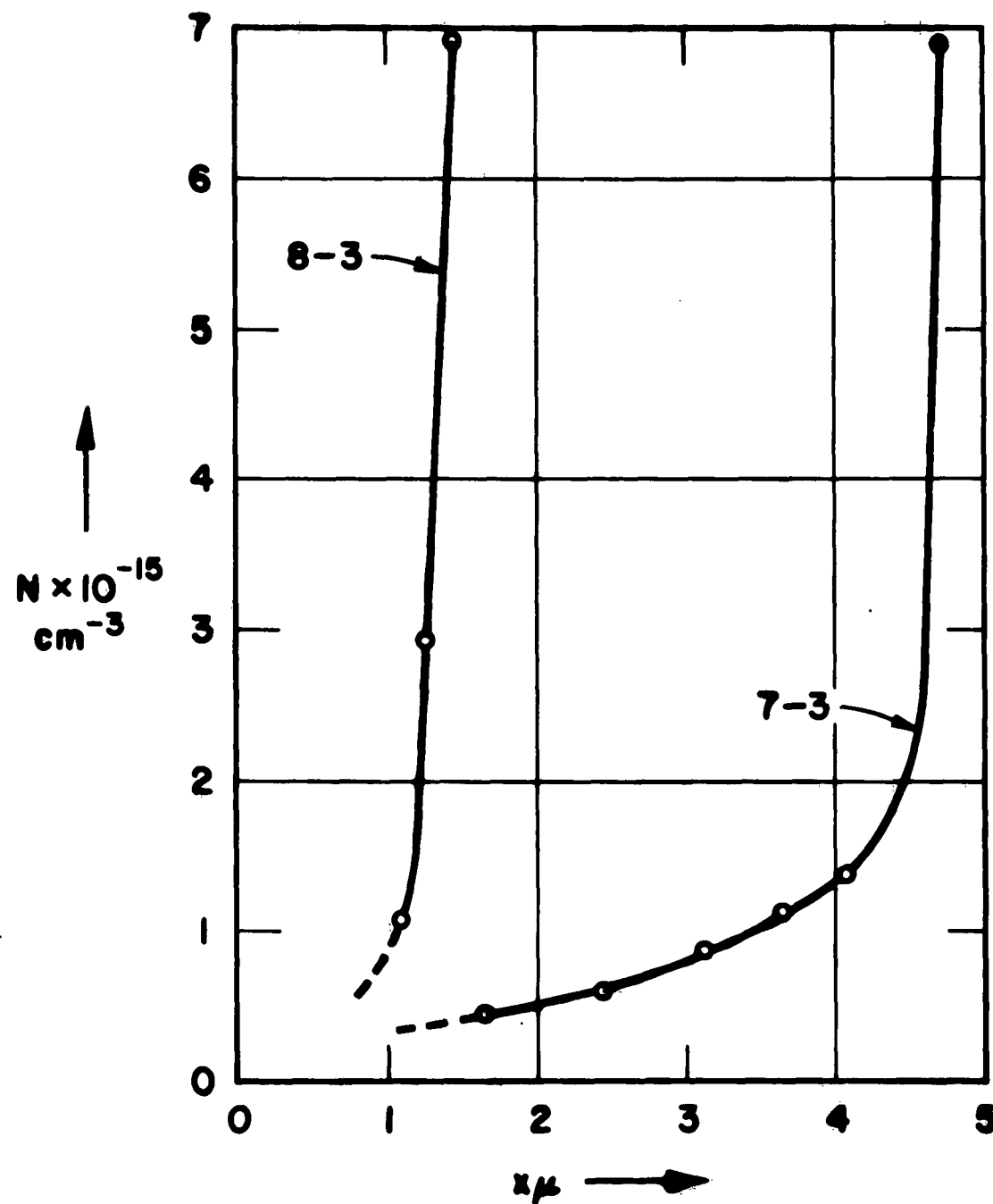


Fig. 3 N^- region density vs distance

8-2-63
50688

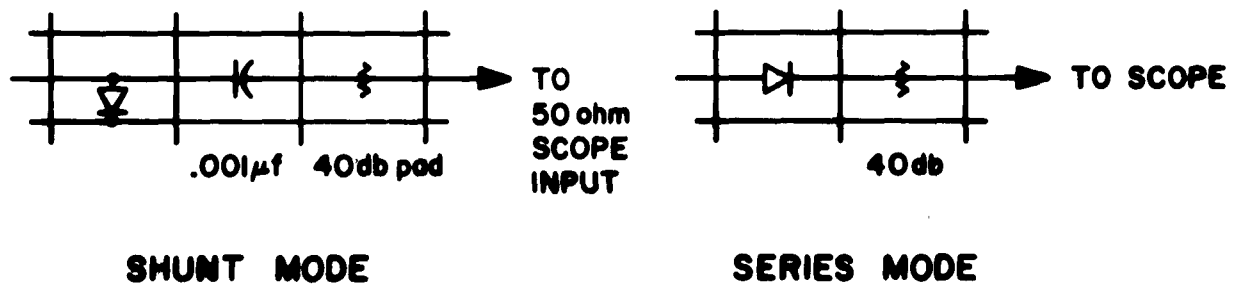
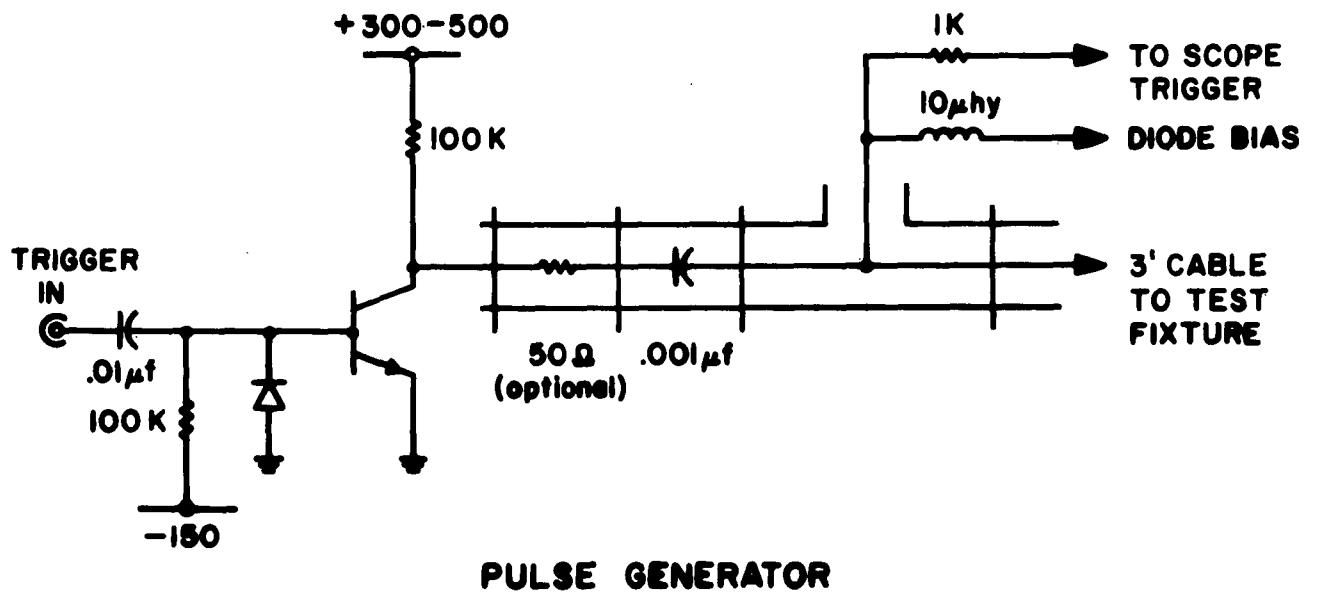


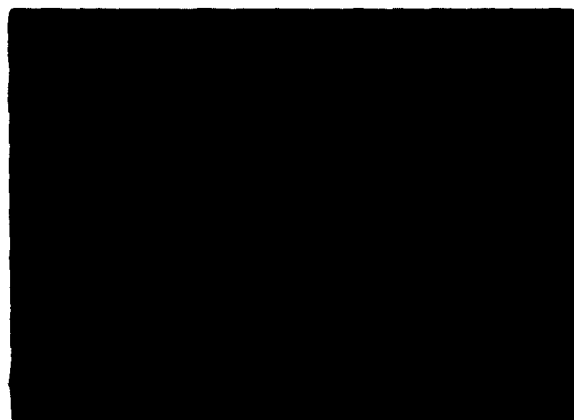
Fig. 4 PIN diode test circuits



10v/cm

DIODE 2-5

$I_r = 2.4A$

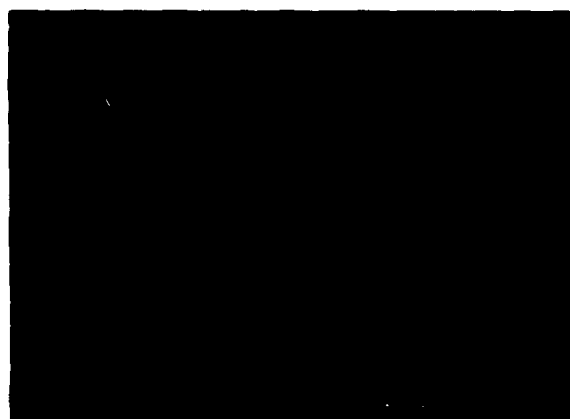


10v/cm

DIODE 5-2

$I_r = 2.4A$

$I_f = 0, 25,$
50, 100, 150,
200 ma



10v/cm

DIODE 5-2

$I_r = 4.8A$

1ns/cm →

Fig. 5 Transition time of previous diodes

8-5-63
50687

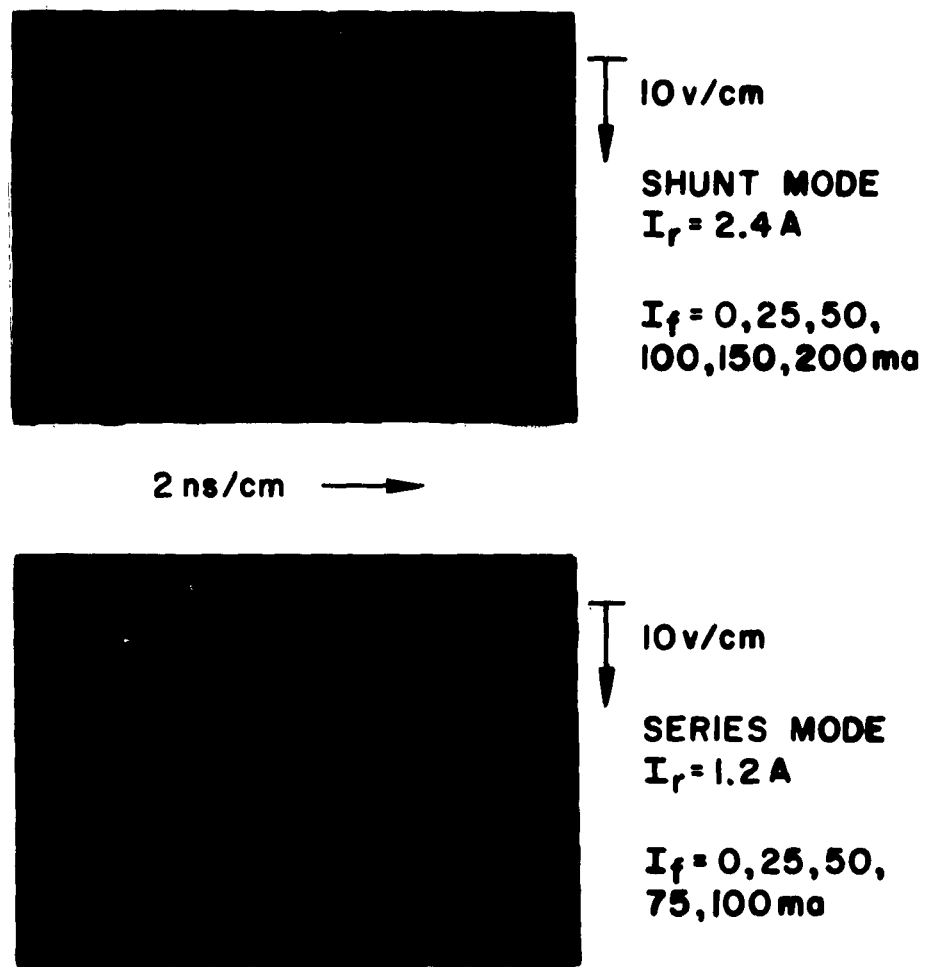


Fig. 6 Diode 7-3 transition times

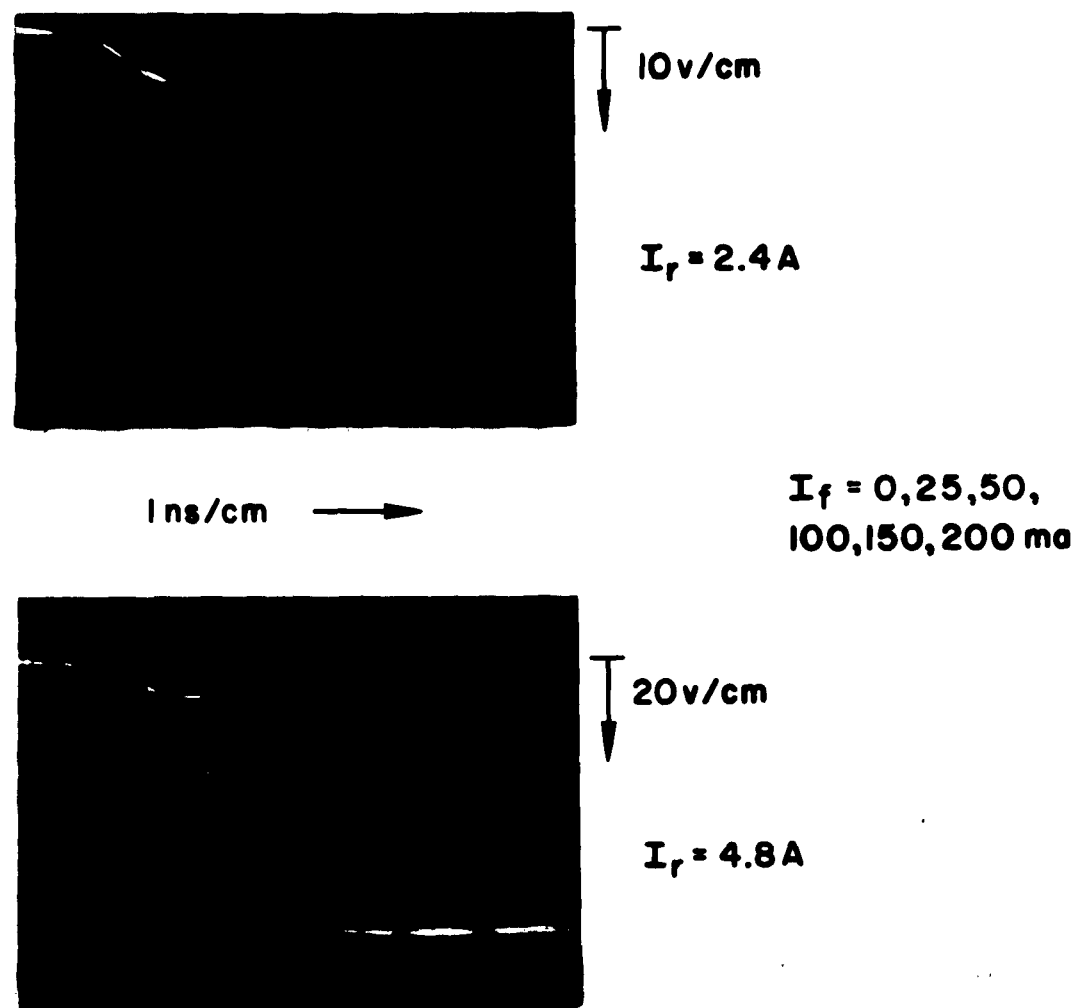


Fig. 7 Diode 8-3 transition times

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